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Water use of *Coffea arabica* in open versus shaded systems under smallholder's farm conditions in Eastern Uganda

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ABSTRACT

Coffee cultivation is a major source of income in East Africa. Increasing temperatures and water scarcity related to climate change are becoming major challenges for coffee production. Therefore, there is an urgent need for sound scientific understanding of the functioning of current coffee cultivation systems and the potential of agroforestry as an adaptation strategy to climate change. In a smallholder coffee farm on Mt Elgon, Uganda, we assessed the effect of three coffee cultivation systems (i.e., Coffee-Open, Coffee-Banana and Coffee-Cordia) on (i) the coffee cultivation environment (e.g. microclimate and soil moisture), (ii) water consumption of coffee, (iii) water consumption of banana (*Musa sp.*) and *Cordia africana* and (iv) water competition or complementary use between coffee and shade tree species. To this end, we monitored sap flux density (J_s) (g cm^{-2} $hour^{-1}$) of coffee, banana and *C. africana* from March 2015 to April 2016, using Granier thermal dissipation method, along with microclimate, soil moisture and rainfall. Shaded systems reduced irradiance by 70% in Coffee-Cordia system and 58% in Coffee-Banana system compared to Coffee-Open system. Maximum temperatures and daily temperature amplitude were on average reduced by 4 °C in both shaded systems compared to Coffee-Open system. Soil water content (SWC) in shaded systems was reduced by 59% in Coffee-Cordia and 6% in Coffee-Banana compared to Coffee-Open. Daily water consumption of coffee plants was 1.2 ± 0.6 l d^{-1} and did not differ between systems. Water use of banana was 3.1 ± 1.8 l d^{-1} and 42 ± 40 l d^{-1} by *C. africana*. Coffee-Banana system had the largest daily transpiration rate, 0.9 ± 0.4 mm d^{-1} per ground area and 0.6 ± 0.4 mm d^{-1} per unit leaf area, followed by Coffee-Cordia with 0.37 ± 0.1 mm d^{-1} (per ground area), 0.36 ± 0.1 mm d^{-1} (per leaf area) and Coffee-Open 0.24 ± 0.1 mm d^{-1} (per ground area), 0.27 ± 0.1 mm d^{-1} (per leaf area). Our results showed that differences in microclimate and SWC between cultivation systems did not influence coffee water use during the monitored year. However, water competition between coffee and shade trees could likely occur in drier years, due to the reduced SWC presently observed in shaded systems. Further research is needed to explore the performance of management practices (mulching, pruning and thinning) in interaction with seasonal weather forecast and appropriate selection of shade species (provision of extra products, reduced water use, fast growth and root zone below 80 cm depth) to match the systems' water requirements with expected soil water availability.

1. Introduction

African countries contribute 12% to global coffee production (FAOSTAT, 2016). Moreover, coffee constitutes up to 30% of the export revenues and foreign exchange earnings of East African countries, such as Uganda (20%) or Ethiopia (30%), where coffee is mostly produced by smallholders (Jassogne et al., 2013; Moat et al., 2017). Thus, coffee is an important cash crop that secures both rural livelihoods and national economy. Climate models project increasing temperatures, changes in rainfall patterns and more frequent extreme events with

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likely strong implications for coffee cultivation in the region (Moat et al., 2017). Coffee sensitivity to climatic variations has been reported by several studies, challenging the sustainability of the sector under climate change and demanding the development of climate-resilient coffee systems (Gay et al., 2006; Zullo et al., 2011; Bunn et al., 2015; Ovalle-Rivera et al., 2015; Craparo et al., 2015; Vaast et al., 2016; Moat et al., 2017). Hence, identifying adaptation strategies, which help to increase the climate-resilience of the coffee cultivation systems in the region, is of urgent need. Finding climate-smart solutions, i.e. practices that help farmers to improve crop productivity, adapt to climate change and support mitigation of greenhouse gas emissions, should receive high priority.

Coffee intercropped with shade trees is regarded as a climate smart agricultural practice (Tscharntke et al., 2011; Vaast et al., 2016). Shade trees help to regulate microclimate by reducing incoming radiation, buffering maximum and minimum temperatures at plot level, and reducing soil evaporation rates. Ideally, this helps to protect the coffee underneath from direct sunlight, preventing temperature extremes and possibly reducing drought stress for the coffee (Barradas and Fanjul, 1986; Muschler and Bonnemann, 1997; Siles et al., 2010; Cannavo et al., 2011; Partelli et al., 2014). Furthermore, shade trees can help to diversify farmers' income and thereby increase food security (Rice, 2008; Vaast and Somarriba, 2014; Mbow et al., 2014a), while capturing CO_2 through biomass accumulation (Beer et al., 1998; Verchot et al., 2007; Mbow et al., 2014b). In addition, shade trees help to maintain biodiversity at landscape level (Garcia et al., 2010; Tscharntke et al., 2011).

Despite the above-mentioned potential benefits, some studies found water competition in agroforestry systems between the understory tree crop and the intercropped shade trees (Beer, 1987; Bayala et al., 2015; Padovan et al., 2018; Abdulai et al., 2018). The risk of water competition between crops and shade trees could pose a severe limitation to agroforestry potential as a climate adaptation strategy, particularly in extreme conditions (Abdulai et al., 2018). Shade trees affect soil water content by increasing transpiration at system level and increasing rainfall interception, potentially reducing water availability for the understory crop (Cannavo et al., 2011; Padovan et al., 2015). However, choice of species with different root architectures may allow a partitioning of soil water uptake from different soil layers, causing minimal competition and reducing water loss through deep percolation (Sanchez 1995; Cannell et al., 1996; Meinzer et al., 2001; Cannavo et al., 2011). In addition, shade trees reduce soil evaporation as demonstrated by Padovan et al (2018), possibly increasing water availability in the upper layers, and hence water use efficiency. Therefore, the role of shade trees in the water balance of agroforestry systems will depend on several factors such as species (rooting depth), planting density and tree size, soil physical properties, amount and pattern of rainfall, and severity of the dry season (Cannavo et al., 2011; Padovan et al., 2018). Given this complexity, designing climate-smart coffee agroforestry systems dealing with these challenges requires robust site and species-specific knowledge to guide their use when aiming to increase their climate resilience (van der Wolf et al., 2016).

Although coffee water use has been previously studied under controlled conditions in green-house experiments (Fanjul et al., 1985; Tausend et al., 2000) and field conditions in research stations (van Kanten et al. 2006; Cannavo et al., 2011; Padovan et al., 2018), our knowledge of coffee water use under smallholder on-farm conditions remains limited, particularly in East Africa. To contribute to closing this knowledge gap, we concentrated our study on three coffee systems (Coffee-Open, Coffee-Banana and Coffee-Tree) prevalent in the Mount Elgon region, Eastern Uganda. These systems differ in coffee tree – shade tree ratio, canopy closure and shade plant species (Liebig et al., 2016; Rahn et al., 2018). Furthermore, they are of particular interest since they provide different services to farmers, such as food and cash in the case of Coffee-Banana systems, or access to fuel wood or timber in the case of Coffee-Tree systems (Rahn et al., 2018). Within the Coffee-Tree systems, the combination of coffee with *Cordia africana* (Coffee-Cordia system) was selected due to the high frequency of *C. africana*, occurring in more than 25% of the agroforestry systems in this region (Rahn et al., 2018).

The main objective of this study was to assess water use patterns of coffee and associated trees under various cultivation systems. To this end, the following specific objectives were set: (i) to understand the effect of different coffee cultivation systems (Coffee-Open, Coffee-Banana and Coffee-Cordia) and a seasonal variation on microclimate and soil moisture in different seasons, (ii) to determine system and seasonal effects on coffee water use, (iii) to quantify water use of banana and *C. africana*, (iv) to estimate combined transpiration of coffee and shade tree species and (v) to determine current water competition or complementary between coffee and shade tree species. We hypothesized that a) shaded systems, Coffee-Banana and Coffee-Cordia better regulate temperature extremes and have lower vapor pressure deficit (VPD) than Coffee-Open system due to reduction of incoming solar radiation, b) shaded systems have higher total transpiration due to the presence of coffee and shade trees, thus shade systems have lower soil water content than open system, and c) coffee water use is higher under shaded than under non-shaded systems due to more suitable microclimate (reduced VPD and solar radiation) in shaded systems.

2. Materials and methods

2.1. Study site

The study was carried out from March 2015 to April 2016 on a smallholder farm on the Western slopes of Mt Elgon, Uganda (1° 15' 52" N 34° 19' 19" E; 1300 m.a.s.l.). The soil was classified as Mollic Nitisol (Colluvic) according to WRB system (see, FAO, 2014), developed from basalt rocks, with a clay texture, pH of 6.5 and organic matter content of 2.58% (De Bauw et al., 2016). Annual mean temperature is 22.6 ± 0.7 °C, annual average maximum temperature 29 ± 1.3 °C and annual average minimum temperature 16 ± 0.4 °C according to Fick and Hijmans (2017) (1970–2000). Annual rainfall sums up to 1243 mm with January, February and December being the driest months and receiving on average 40 mm month^{-1} (Supplementary material, figure A.1). Highest amounts of rainfall were reported in April and May, both with more than 100 mm month^{-1} (Fick and Hijmans, 2017) (1970–2000).

The coffee plot had a total area of 1941 m^2 with a variable slope from 22% to 32%. Herbicide applications (Glyphosate 48 E) were done three times a year (~10 l ha^{-1}), no fertilizer was applied; neither pruning nor other further management was carried out during the experiment span. On the farm, three different coffee systems were distinguished according to the abundance of banana (Musa sp.) and shade trees (*C. africana*): Coffee-open (CO), Coffee-banana (CB) and Coffee-Cordia (CC) and were distributed along the slope (at the highest point CC, CO and CB at the lowest point) (Supplementary material, figure A.2). The CB system had twice as many coffee trees per hectare compared to the other two systems (Table 1). Although this high coffee tree density is atypical in the area (Rahn et al., 2018), the plot was selected due to its proximity to the other systems (CO and CC), since sap flow sensors needed to be connected to a data logger and a power source. *Cordia africana* trees were only found in the CC system. Coffee stem diameter measured at 30 cm above the stump varied between 2.2 and 2.3 cm in all three systems, and the average number of stems per coffee tree was between 2.6 and 3.5. Coffee individual leaf area (based on 50 randomly selected leaves per system) was significantly higher in the CC system compared to CB and CO (Table 1). Individual leaf area was calculated by multiplying width (cm), length (cm) and a correction factor of 0.7243 (according to Padovan et al., 2018).

Table 1
Characteristics of the three coffee systems studied (CO = coffee-Open, CB = Coffee-Banana, CC = Coffee-Cordia). LAI = leaf Area Index, BA = Basal Area, SWA = Sap Wood Area.

Variable Plot characteristics	CO	CB	CC
Area (m^2)	400[a]	400[a]	1000[a]
Coffee density (Trees ha^{-1})	1875	3900	1950
Banana mat density (mats ha^{-1})	–	975	–
Banana stem density (stems ha^{-1})	–	2450	–
Cordia africana density (Trees ha^{-1})	–	–	50
N° Coffee Stems per coffee plant	3.1 ± 0.9	3.5 ± 1.2	2.6 ± 0.9
Coffee Stem Diameter (cm)[b]	2.20 ± 0.4	2.25 ± 0.4	2.31 ± 0.5
Individual coffee leaf Area (cm^2)	52.1 ± 29	40.2 ± 25	87 ± 34
LAI (System/Shade/Coffee)[c]	1.2/0.3[d]/0.9	2.7/1.2/1.5	2.3/1.5/0.78
Coffee BA (cm^2 $Tree^{-1}$)	12.5 ± 6.5	14.1 ± 6.4	10.7 ± 5.1
Coffee BA (m^2 ha^{-1})	2.35	5.5	2.1
Banana BA (m^2 ha^{-1})[e]	–	61.6	–
Cordia africana BA (m^2 ha-1)	–	–	25.84
Slope %	27	22	32
Coffee SWA (cm^2 $stem^{-1}$)[b]	3.8 ± 0.1	3.9 ± 0.1	4.2 ± 0.2
Coffee SWA (cm^2 $stem^{-1}$) [f]	12.7 ± 2.5	10.0 ± 1.6	10.5 ± 3.2
Musa sp. SWA (cm^2 $tree^{-1}$)	–	75.9 ± 19.8	–
Cordia africana SWA (cm^2 $tree^{-1}$)	–	–	1061 ± 921
Soil Properties (4 Samples per System)			
Horizon A (0-40 cm)			
pH	6.45 ± 0.1	6.45 ± 0.1	6.25 ± 0.1
Organic Matter %	4.9 ± 3.4	5.8 ± 1.7	4.6 ± 2
Sand/Clay/Silt %	33/41/25	29/41/29	30/49/20
Texture Class	Clay	Clay	Clay
Bulk Density (g cm^{-3})	1.3 ± 0.1	1.1 ± 0.1	1.3 ± 0.0
Total Porosity %	50.6 ± 5.0	56.9 ± 5.3	49.7 ± 2.3

[a] Between CO system and CC system there was a buffer area of 141 m^2. Supplementary material, figure A.2.
[b] Measured on 50 stems.
[c] LAI measured with LiCOR 2200C as described in Section 2.3.
[d] This LAI of shade in CO might be due to light intercepting branches of trees outside the studied plot.
[e] Calculated based on: average BA of individual stems (n = 8) * banana mat density * 1.5.
[f] Calculated based on monitored coffee stems (n = 15, 5 stems per system).

2.2. Microclimate

In each system, two sensors for measuring air temperature (Ta) and relative humidity (RH) (Thermochron iButton, Coldchain) were installed inside the coffee canopy at 1.5 m above the ground. Temperature (Ta) and relative humidity (RH) were recorded every 30 s and averaged every 30 min. Photosynthetic radiation was measured in every system using two quantum sensors per system (SOLEMS-PAR-CBE80, Palaiseau, France), which were placed above the coffee canopy but below the shade tree canopies. Rainfall was measured using a tipping bucket rain gauge (Model ARG, 100, Campbell Scientific Inc, Logan, UT, USA) with a resolution of 0.2 mm, which was placed in an open area at 2 m above ground. All sensors (except Ta/RH sensors) were connected to a data logger (CR1000 with AM 16/31 multiplexer Campbell Scientific Inc. Logan, UT, US), values were recorded every 30 s and averaged every 30 min. Photosynthetic radiation sensors were later on calibrated in the green house with LI-250 A light meter. Additionally, rainfall from the last 10 years was obtained from the closest weather station (Buginyanya, 1° 16' 48" N 34° 22' 16" E; 1800 m.a.s.l), located at a distance of 5.7 km to the study site. Vapor pressure deficit (VPD) and reference evapotranspiration (ET_0) was calculated via the Penman-Monteith equation (Equation A.1, supplementary material) (Allen et al., 1998). Daily radiation was derived from irradiance (W m^{-2}) following the equation proposed by Allen et al (1998) (Equation A.2, supplementary material). Months in which the monthly ratio rainfall/ET_0 was > / = 1 were considered as wet months, whereas months in which the ratio was < 1 were considered as dry months according to Cannavo et al. (2011).

Since it was expected that the response of water use (Q_c) to vapor pressure deficit (VPD) and irradiance (Irr) varied with soil water content (SWC) (Carr, 2001; DaMatta and Ramalho, 2006), we examined those responses during three distinctive periods: wet period (low VPD and high SWC), early dry period (high VPD and high SWC) and late dry period (high VPD and low SWC).

2.3. Soil water content

Soil water content (SWC) was monitored every two weeks with a Sentek soil water probe (Diviner 2000). Two access tubes of 1.60 m depth were installed in each system and volumetric water content (mm cm^{-3}) was recorded at 10 cm intervals. The default calibration equation provided by Sentek was used to convert device readings to volumetric soil moisture content (Scaled Frequency = 0.2746 * (volumetric water content ^ 0.3314) + 0) (Sentek Pty Ltd, 2009). Total water content was calculated as the cumulative sum of volumetric water content across the layers and expressed in mm.

2.4. Leaf Area index

Leaf area index (LAI) was measured with a LICOR 2200C plant canopy analyzer (Model LAI-2270C, SR.NO.PCA-3940, LICOR) five times during the study period (Jul 2015, Sep 2015, Nov 2015, Feb 2016 and Mar 2016). At each sampling time, two measurements per system were conducted. One measurement in which the sensor was placed below coffee trees for capturing system LAI (shade LAI + coffee LAI) and during the second measurement, in which the sensor was placed above coffee trees and below shade trees, to capture shade LAI. Coffee LAI was determined by subtraction of shade LAI from system LAI. Each measurement consisted of 20 points below the foliage (either below coffee or below shade), distributed systematically in the system/plot and 2 points in the open area, as recommended by Li-COR, Inc. (2009).

2.5. Quantifying water use

Sap flux density was measured with thermal dissipation probes after Granier (1987). Sensors consisted of two probes with a length of 2 cm each. Inside each probe, a thermocouple (copper-constantan alloy) is located in the middle (at 1 cm). Furthermore, one of the probes was heated by a copper filament rolled over the length of the probe, while the other remained unheated. Each probe was inserted radially into the trunk sapwood. The sensor pairs were placed at a distance of 10–15 cm from each other. In the case of coffee trees, the upper probes were place at a distance of 30 cm from the stump. For *C. africana* trees, probes were inserted at a height of 2 m from the ground. Since bananas develop a pseudostem formed by leaves which grow fast and do not have a distinct water conductive area, the sensors were inserted in the central cylinder of the corm as suggested by Lu (2002). The heated probe was inserted into the upper region of the central cylinder, beneath the cambium region at a depth of 1–3 cm in the inner central cylinder. The unheated probe was inserted in the cortex, around 1–2 cm away from the heated probe. The upper probes (downstream sensor) were constantly heated by batteries recharged via a solar panel, while the lower probe (upstream sensor) remained unheated, serving as a reference. The non-flux condition was determined daily as the highest ΔV recorded in the period of 24 h for each sensor. Each pair of sensors was connected to a data logger (Data Logger CR1000 and AM 16/31 multiplexer Campbell Scientific Inc. Logan, UT, US) and values were recorded every 30 s and averaged every 30 min. Five coffee plants in each system (CO, CB and CC) were monitored from March-2015 to April-2016. Additionally, five banana pseudo stems (*Musa* sp.) and three *C. africana* trees (with five sensors) were monitored. Due to large size of two of the 3 C. africana individuals (DBH > 1 m), we decided to place two sensors in

each individual to account for possible radial variations of sap flux density (Delzon et al., 2004). Sensors were protected from rain and extreme temperatures with isolation sheets. Sap flux density (J_s) (g cm^{-2} $hour^{-1}$) was calculated based on the equation of Granier (1987). We did not perform any specific calibration of the equation.

$$J_s\ (g\ cm^{-2} hour^{-1}) = 3600 * 0.0119 * \left(\frac{max\Delta V - \Delta V}{\Delta V}\right)^{1.231} \quad (1)$$

Max ΔV was determined on a daily basis as the highest value in 24 h. For estimating mean sap flux density (mean J_s) only values recorded between 6:00 am (sunrise) to 7:00 pm (sunset) were considered. Hourly sap flow (Q) (l $hour^{-1}$) was derived from the integration of sap flux density over the conductive area or sap wood area (SWA):

$$Q\ (l\ hour^{-1}) = \frac{Js\ (g\ cm^{-2} hour^{-1}) * SWA\ (cm^2)}{1000} \quad (2)$$

Daily tree water use (Q_c) (l d^{-1}) was calculated by summing up the obtained Q values during the day (between sunrise and sunset) following the Eq. (3). To determine daily water use of coffee trees, Q_c was multiplied by the number of stems per tree.

$$Q_c\ (l\ d^{-1} = \sum_{i=6:00am}^{7:00pm} Qi) \quad (3)$$

For determining conductive sapwood area of coffee, the monitored stems were cut and placed in water with methyl orange until the water was evaporated. No coloring distinction that indicated heart wood was found in monitored stems, thus the entire basal area of the coffee trees was considered to be conductive. For *C. africana,* wood cores (5 mm diameter) were extracted from the different individuals (4–8 cores per tree) in different directions. The sapwood had a distinguished color from the heartwood, which allowed to directly determining sapwood depth ($depth_{sw}$). Later on, measurements were confirmed through microscopic inspection of the core samples. The sapwood area of *C. africana* was calculated based on the total radius (R_t) and the sapwood depth (SW_{Depth}) using the following equation:

$$SWA\ (cm) = \pi * (2 * R_t * SW_{depth} - (SW_{depth})^2) \quad (4)$$

For banana, the sap wood area corresponds to the area of the central cylinder, thus it can be estimated from the diameter of the central cylinder (D_{cc}) (Eq. (5)). D_{cc} is determined based on the relationship between the diameter of the corm (D_c) and diameter of the central cylinder (D_{cc}) as suggested by Lu (2002):

$$Banana\ SWA\ (cm^2) = \pi * \frac{Dcc^2}{4} \quad (5)$$

$$Dcc\ (cm) = 0.5973 * Dc\ (cm) \quad (6)$$

Transpiration per ground area (mm d^{-1}) was estimated by multiplying water use (Q_c) (l d^{-1}) by the stand density (trees ha^{-1}) and transpiration per unit leaf area (mm d^{-1}) was estimated by dividing transpiration per ground area (mm d^{-1}) by LAI (obtained as described in section 2.3) (m^2 m^{-2}) (Hernández-Santana et al., 2009).

2.6. Data analysis

Statistical analysis was conducted using R version 3.3.3 (R Development Core Team, 2015). Data were analyzed using linear mixed models (Package lmer, lmerTest and multicomp) (Bates et al., 2015; Kuznetsova et al., 2017). To evaluate system effects (CO, CB and CC) on microclimatic parameters at daily and hourly resolution (mean temperature, max temperature, min temperature, radiation, vapor pressure deficit and soil moisture), the system was used as a fixed effect and the date as random effect (microclimate variable ~ System + (1| Date). To evaluate system (CO, CB or CC) or period (Wet, early dry or late dry) effect on coffee mean sap flux density (J_s), coffee water use (Q_c) and coffee transpiration per unit basal area (Tr basal area) and transpiration per unit leaf area (Tr per unit leaf area), system or period was used as fixed effects and coffee stem ID and date were used as random effects (mean Js ~ System or season + (1|ID) + (1|Date)). The same model was used to evaluate period effect on J_s, Q_c anf Tr per unit LA of banana and *C. africana*. When significant differences were encountered, we used a post-hoc test using the "multicomp" package and "Tukey" as the multiple-comparison procedure to identify significant difference among systems and/or periods (Hothorn et al., 2008). Data were evaluated whether they fulfill the assumptions of homogeneity of variance and normality, and transformed whenever necessary. All figures were produced with package ggplot2.

3. Results

3.1. Microclimate

Daily mean temperature during the study period from 01 March 2015 to 16 April 2016 was 22.7 ± 2.3 °C, and precipitation summed up to 1699 mm. Average daily VPD was 0.9 ± 0.7 kPa and daily radiation 7.8 ± 2.8 MJ m^{-2} d^{-1}. Calculated daily average reference evapotranspiration (ET_0) was 4.1 (± 1.8) mm d^{-1}. Monthly ET0 was in the order of 123 (± 54) mm per month and exceeded monthly rainfall in March, July, and August 2015, as well as during the dry period from December 2015 to March 2016 (Fig. 1A). April, May, Jun, Sep, Oct, Nov 2015, and April 2016 were considered as wet periods, (monthly rainfall > monthly ET0). Dry months (monthly rainfall < monthly ET0) were divided into early dry (July, Aug., Dec. 2015, and Jan 2016) and late dry (March 2015, Feb. and March 2016), depending on the reduction of soil water content (Fig. 1B).

Mean temperature, maximum temperature, irradiance and vapor pressure deficit were significantly higher in CO than in CC and CB, averaged over the whole study period (supplementary material Table A.1) and in each period separately (Table 2). CC displayed lowest Ta max and highest Ta min, as well as the lowest amplitude (Ta max –Ta min) and lowest irradiance. CB system had the lowest daily mean VPD and Ta mean, and an intermediate irradiance (See Table 2). Temperature, vapor pressure deficit and irradiance followed a strong increase during February and March (Late dry) for all systems (Fig. 2).

Nevertheless, despite significant temperature differences between systems, differences remained below 1 °C for Ta mean and Ta min (Table 2). Differences for Ta max were larger and reached up to 4 °C when between comparing CO and CC. The temperature amplitude between systems ranged accordingly from 4 to 5 °C. Daily Ta patterns revealed temperatures above 30 °C from 10:00 to 18:00 h in all systems during the late dry period. VPD in CO and CC did not significantly differ during late dry period, while VPD was recorded to be significantly lower in CB for all periods (Table 2). The highest VPD was recorded between 14:00 and 16:00 and remained below 2 kPa for the wet and early dry periods. During the late dry period, however, VPD surpassed 2 kPa already at 10:00 h in all systems, and reached values as high as 4.5 kPa (Fig. 2). As reported in several studies, 2 kPa is marked as a relevant threshold for stomata closure of coffee (> 1.6 kPa) and many other species (Butler, 1977; Fanjul et al., 1985; Gutierrez et al., 1994; Kanechi et al., 1995; Carr, 2001; DaMatta and Ramalho, 2006; van Kanten and Vaast, 2006; Jung et al., 2011).

Highest irradiance was recorded in CO during all periods (Table 2). Irradiance was higher in CB than in CC during the wet and early dry period; however, no significant differences between these two systems were found during the late dry period (Table 2). Irradiance increase in CB had 1 h lag-phase compared to CO and CC in the first hours of the day, probably due to the topography of the plot (Fig. 2).

3.2. Soil water content

Total soil water content (SWC) (down to 90 cm depth) was the

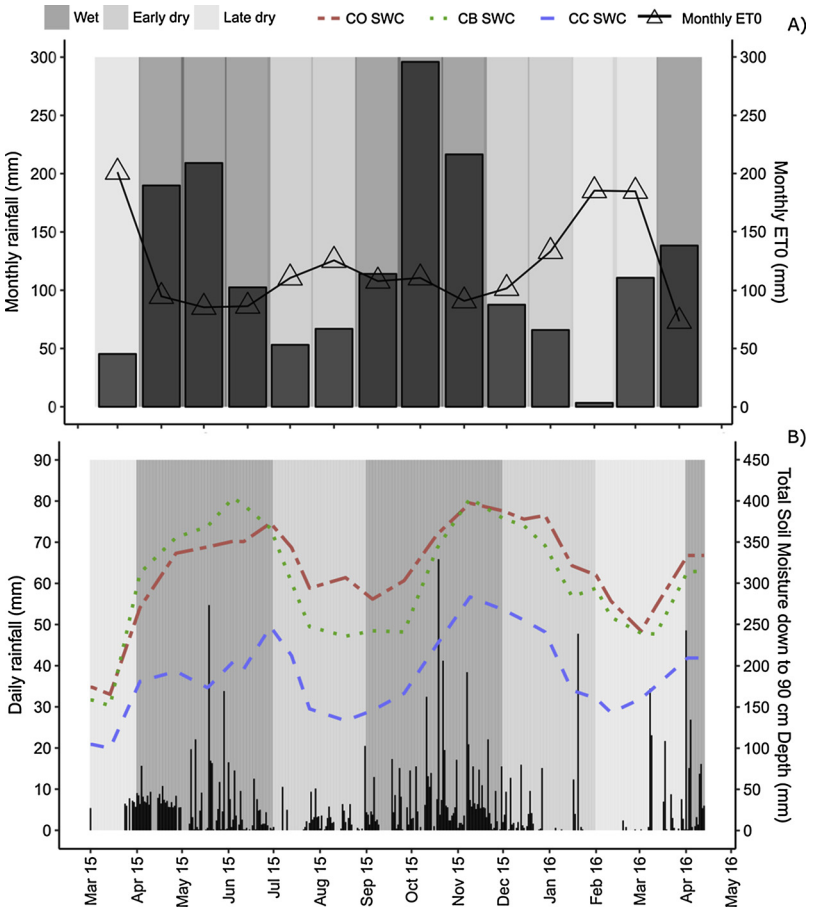

Fig. 1. A) Monthly rainfall totals (mm) (Black bars) and monthly totals of potential evapotranspiration (solid line with open triangles). B) Daily rainfall (mm d^{-1}) (black bars, soil water content (SWC) in the 0–90 cm layer per system (Coffee-Open = CO (Red) (- – -), Coffee-Banana = CB (Green) (….) and Coffee-Cordia = CC (Blue) (– – –)) at the experimental site for the study period (March 2015 - April 2016). Background color represents the period, Wet (dark grey) (April, May, Jun, Sep, Oct and Nov 2015, Apr 2016), early dry (intermediate grey) (Jul, Aug and Dec 2015, Jan 2016) and late dry (light grey) (Mar 2015, Feb and Mar 2016) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

highest in CO and varied between periods from 340 mm (wet) to 249 mm (late dry). CC had the lowest total SWC in all periods compared to CO and CB (Table 2). Water uptake by plants occurred mostly in the first 90 cm. Between 20 to 80 cm depth, CO had higher SWC (30–40 mm) per depth compared to CC (10–20 mm), and this trend was consistent during the early dry period and wet period (Fig. 3). In the first 30 cm, SWC in CB decreased during the early dry period and late dry period to 10–30 mm per depth and during the wet period to 20–30 mm per depth, while for CO such decreases were only observed during the late dry period. Below 90 cm depth, SWC values of the CO and CC remained at similar levels (30–40 mm per depth) during the wet period, while during the dry period, CC dropped below 30 mm per depth between 100 cm and 130 cm depth (Fig. 3). Due to technical problems, no data were available for CB below 90 cm.

3.3. Water use

Coffee mean sap flux density (J_s) averaged over the study period, was 2.6 ± 2 g cm^{-2} h^{-1} in Coffee-CO, 3 ± 2.6 g cm^{-2} h^{-1} in Coffee-CB and 2.7 ± 2.4 g cm^{-2} h^{-1} in Coffee-CC and did not differ significantly

Table 2
Total soil water content down to 90 cm (mm), mean vapor pressure deficit (VPD) (kPa), daily irradiance (Irr) (6:00 am – 7:00 pm) (W m^{-2} d^{-1}), mean temperature (°C), maximum temperature (°C), minimum temperature (°C) and temperature amplitude (T max – T min) (°C) for three different periods Wet (April, May, Jun, Sep, Oct and Nov 2015, Apr 2016), early dry (intermediate grey) (Jul, Aug and Dec 2015, Jan 2016) and late dry (light grey) (Mar 2015, Feb and Mar 2016).Letters refer to significant differences ($p < 0.05$) between systems in each period.

Wet			Early dry			Late dry		
CO	CB	CC	CO	CB	CC	CO	CB	CC
Total Soil water content (SWC) (Down to 90 cm depth)								
340 ± 35 ^{a}	340 ± 52 ^{b}	206 ± 38 ^{c}	335 ± 33 ^{a}	298 ± 49 ^{b}	191 ± 46 ^{c}	249 ± 48 ^{a}	237 ± 44 ^{b}	151 ± 29 ^{c}
VPD (kPa)								
0.5 ± 0.25 ^{a}	0.3 ± 0.2 ^{c}	0.4 ± 0.2 ^{b}	0.8 ± 0.3 ^{a}	0.6 ± 0.2 ^{c}	0.7 ± 0.3 ^{b}	1.9 ± 0.8 ^{a}	1.8 ± 1 ^{b}	1.8 ± 0.8 ^{a}
Irradiance (W m^{-2})								
1419 ± 827 ^{a}	689 ± 711 ^{b}	233 ± 253 ^{a}	1872 ± 582 ^{a}	599 ± 475 ^{b}	386 ± 186 ^{c}	2348 ± 1171 ^{a}	1038 ± 766 ^{b}	1034 ± 719 ^{b}
Mean temperature (°C)								
21.5 ± 4 ^{a}	20.8 ± 3.2 ^{c}	21.1 ± 2.6 ^{b}	22.3 ± 4.8 ^{a}	21.4 ± 3.9 ^{c}	21.9 ± 3.2 ^{b}	26.1 ± 6.2^{a}	25.9 ± 5.9 ^{b}	25.9 ± 5.2 ^{a}
Max temperature (°C)								
30.3 ± 3.7 ^{a}	27.3 ± 3.4 ^{b}	26.1 ± 2.6^{c}	32.0 ± 3.1 ^{a}	28.7 ± 2.5 ^{b}	27.7 ± 2.2 ^{c}	37.8 ± 4.2 ^{a}	36.8 ± 4.5 ^{b}	34.8 ± 3.9 ^{c}
Min temperature (°C)								
17.4 ± 0.7 ^{a}	17.5 ± 0.7 ^{a}	18.0 ± 0.7 ^{b}	17.3 ± 0.9 ^{b}	17.2 ± 0.6 ^{c}	18.1 ± 1.0 ^{a}	19.2 ± 1.1 ^{c}	19.5 ± 1.3 ^{b}	20.0 ± 1.4 ^{a}
Temperature amplitude (ΔTa) (°C)								
12.8 ± 3.8 ^{a}	9.8 ± 3.4 ^{b}	8.2 ± 2.5 ^{c}	14.6 ± 3.3 ^{a}	11.5 ± 2.5 ^{b}	9.5 ± 2.2 ^{c}	18.6 ± 4 ^{a}	17.3 ± 4.2 ^{b}	14.8 ± 3.3 ^{c}

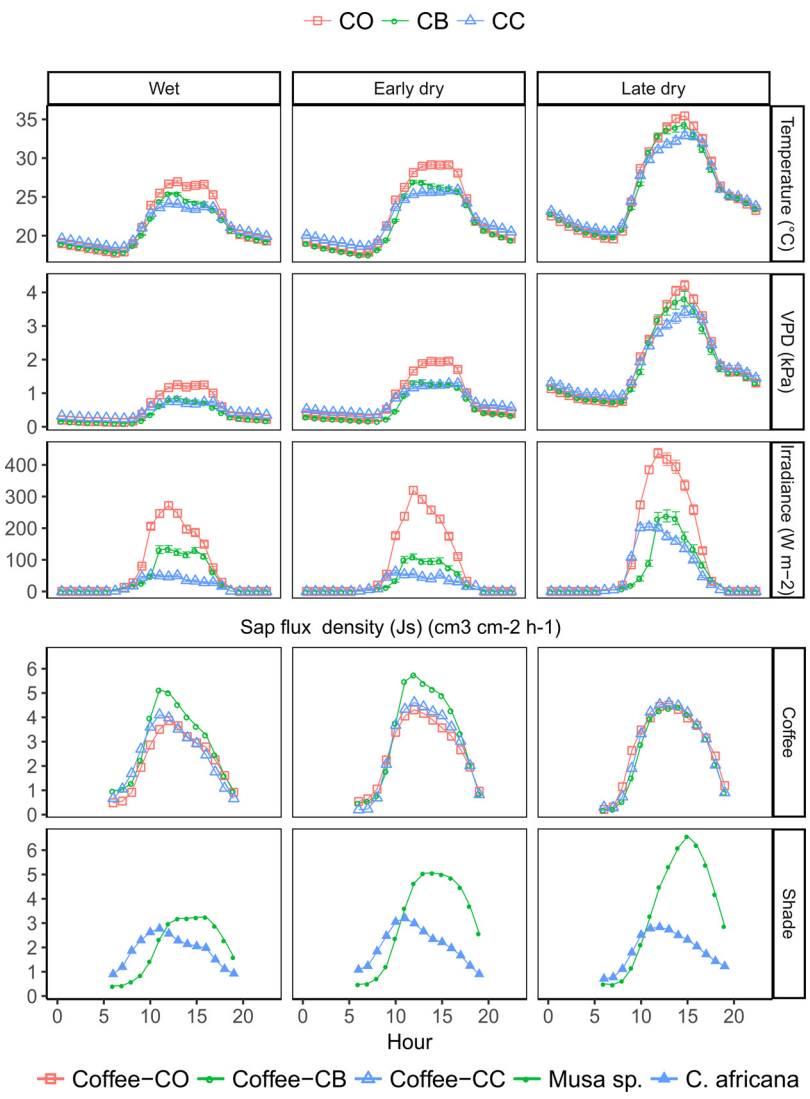

Fig. 2. Daily patterns of Temperature (°C), vapor pressure deficit (VPD) (kPa),irradiance (W m^{-2}) and sap flux density (cm^3 cm^{-2} h^{-1}) for three periods: Wet (April, May, Jun, Sep, Oct and Nov 2015, Apr 2016), early dry (intermediate grey) (Jul, Aug and Dec 2015, Jan 2016) and late dry (light grey) (Mar 2015, Feb and Mar 2016).In three different systems (Coffee-Open = CO (Square) (Red), Coffee-Banana = CB (Circle) (Green) and Coffee-Cordia = CC (Triangle) (Blue)and coffee (Coffee − CO (Empty square) (red), Coffee-CB (empty circle)(Green), Coffee − CC (empty triangle)(Blue), Musa sp. (Fill circle)(Green) and *C. africana* (Fill triangle)(Blue). Line indicates mean values and error bar indicates standard error**. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).**

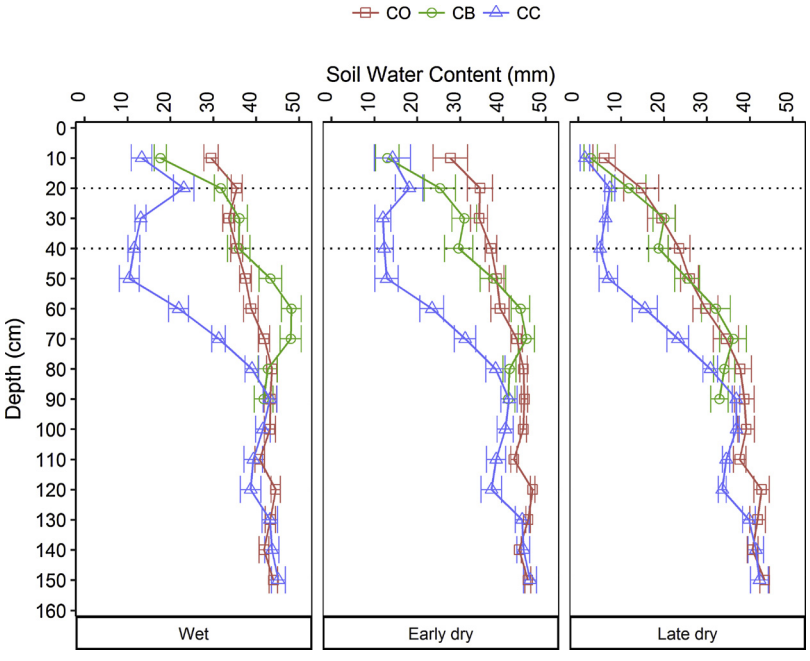

Fig. 3. Soil water content (mm) per 10 cm depth interval during distinct periods (wet, early dry period and late dry period) down to 150 cm depth except for CB system for which measurements were only available down to 90 cm depth. (Coffee-Open = CO (Square)(Red), Coffee-Banana = CB (Circle) (Green) and Coffee-Cordia = CC (Triangle) (Blue). Line indicates mean values and error bar indicates standard error. Dotted lines indicate 20 cm and 40 cm depths (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

between systems. Coffee mean J_s did also not differ between systems when compared for each period separately (wet, early dry, late dry, Table 4). A significant increase in coffee mean J_s occurred in Coffee-CO during the early and late dry periods, while Coffee-CB mean J_s increased during the early dry compared to wet period. And decreased again during the late dry period (Table 4). For Coffee-CC, highest mean J_s was recorded during the early dry period, and it was significantly larger than mean J_s during the wet period. No significant differences in mean J_s of Coffee-CC were found between mean early period and late dry period or between late dry period and wet period. Coffee daily Q_c per tree (l d^{-1}) was not significantly different between systems with mean daily values of 1.3 ± 0.55 (l d^{-1}) for Coffee-CO, 1.4 ± 0.76 (l d^{-1}) for Coffee-CB and 1.0 ± 0.63 (l d^{-1}) for Coffee-CC. Furthermore, no significant system effect on Q_c was found for any of the three distinct periods (Table 4). Q_c of Coffee-CO and Coffee-CC significantly increased during early and late dry period compared to the wet period, namely by 18% for Coffee-CO and 19% for Coffee-CC. On the other hand, Q_c of Coffee-CB increased 14% during the early dry period and decreased again during the late dry period.

Coffee leaf area index (LAI) increased during the early dry period when compared to the wet period in Coffee-CO by +21% and Coffee-CC by +25%. On the other hand, LAI of Coffee-CB decreased by -11% in the early dry period (Fig. 4). During the late dry period, LAI decreased in Coffee-CO by -28% and Coffee-CB by -36%. Whereas, LAI of Coffee-CC increased by +35% during the late dry season. Daily coffee transpiration per unit leaf area (mm d^{-1}) averaged over the study period did not differ between systems. On the other hand, daily coffee transpiration per unit leaf area varied between periods differently depending on the system. In CB, coffee increased transpiration per unit leaf area by 33% during the early and late dry period compared to the wet period. In CO, coffee increased transpiration per unit leaf area during the late dry period by 70% compared to transpiration per leaf area during the wet period. On the other hand, Coffee-CC presented higher transpiration rates during the wet period, compared to the early dry and late dry periods (Fig. 4). Variations in coffee transpiration per leaf area corresponded to variations in LAI.

Coffee transpiration per ground area was significantly higher in CB than in CO and CC, which corresponded with higher coffee tree density (Fig. 4).

Daily water use (Q_c) was significantly different between shade species (p-value < 0.001). The shade tree species *C. africana* had a higher daily water use rate per tree (41 ± 391 d^{-1}) than banana (3 ± 21 d^{-1}). Although, mean J_s was lower for *C. africana* than for banana, it did not differ significantly from each other (Table 4). Banana J_s however differed significantly across periods. Lowest values were recorded during the wet period, while highest values occurred during the late dry period (Table 4). Mean J_s of *C. africana*, on the other hand increased significantly during the early dry period; and decreased during the late dry period and the wet period (Table 4). Banana transpiration per ground area was significantly larger than *C. africana* transpiration per ground area only for the late dry period (Fig. 4). *Cordia africana* transpiration per unit leaf area increased during the late dry period compared to the wet and early dry periods due to leaf senescence (Fig. 4).

CB system had the largest system transpiration per ground area (0.9 ± 0.4 mm d^{-1}) and per unit leaf area (0.6 ± 0.4 mm d^{-1}) (p-value = < 2.26 e^{-16}), which was consistent among all three periods (Fig. 4). CC transpired 0.37 ± 0.1 mm d^{-1} per ground area and 0.36 ± 0.1 mm d^{-1} per unit leaf area, which was significantly larger than the transpiration rates of CO that displayed values of 0.24 ± 0.1 mm d^{-1} per ground area and 0.27 ± 0.1 mm d^{-1} per unit leaf area. Coffee contributed on average 55% to the system transpiration per ground area in CB and 47% in the CC system, whereas bananas contributed up to 45% and *Cordia africana* up to 53% of the system transpiration per ground area (Fig. 4). For calculation of transpiration it was assumed that weeds were absent.

3.4. Influence of VPD on hourly sap flux density for different periods

Bananas showed a linear increase in Js when VPD was increasing

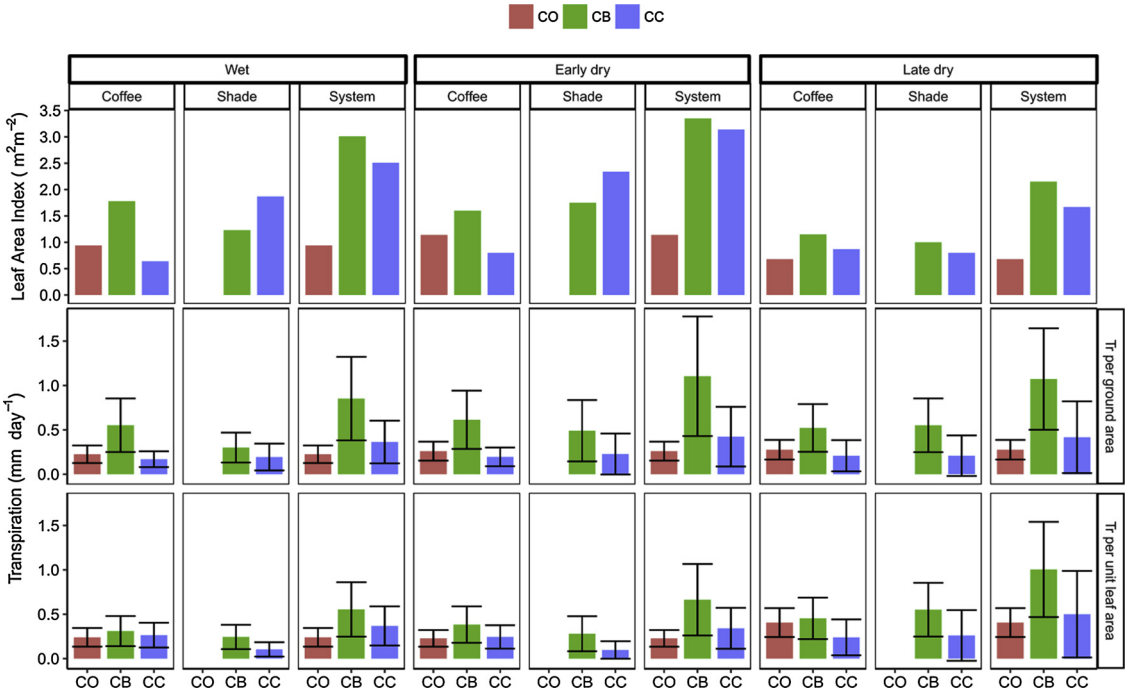

Fig. 4. Leaf area index (LAI), transpiration (Tr) per ground area (Q_c * Tree density) and transpiration(Tr) per unit leaf area (Tr per ground area/LAI) for coffee, shade (Musa sp in CB and Cordia africana in CC) system (Coffee + shade) in three systems (Coffee-Open = CO (Red), Coffee-Banana = CB (Green) and Coffee-Cordia = CC(Blue)), for three distinct periods Wet (April, May, Jun, Sep, Oct and Nov 2015, Apr 2016), early dry (Jul, Aug and Dec 2015, Jan 2016) and late dry (Mar 2015, Feb and Mar 2016) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 3
Mean J_s, daily Q_c per stem and per coffee tree for coffee in each system (Coffee – CO, Coffee-CB, Coffee – CC for each of the three periods Wet (April, May, Jun, Sep, Oct and Nov 2015, Apr 2016), early dry (Jul, Aug and Dec 2015, Jan 2016) and late dry (Mar 2015, Feb and Mar 2016). Capital letters indicate significant differences between systems for each period. Small case letters indicate significant differences across seasons for each system. Significances at p-value < 0.05.

	Wet			Early dry			Late dry		
	Coffee-CO	Coffee-CB	Coffee-CC	Coffee-CO	Coffee-CB	Coffee-CC	Coffee-CO	Coffee-CB	Coffee-CC
N° of monitoring Days *	182	179	152	123	123	89	85	86	86
Mean Js ($g\ cm^{-2}\ h^{-1}$)	2.35 ± 1.05 ^{A,b}	3.02 ± 1.40 ^{A,b}	2.54 ± 1.37 ^{A,b}	2.73 ± 1.15 ^{A,a}	3.34 ± 1.45 ^{A,a}	2.8 4 ± 1.17 ^{A,a}	2.92 ± 1.21 $^{A,\ a}$	2.70 ± 1.21 ^{A,b}	2.92 ± 2.03 ^{A,ab}
Daily Qc ($l\ d^{-1}$) **per stem**	0.38 ± 0.16 ^{A,b}	0.40 ± 0.22 ^{A,b}	0.33 ± 0.17 ^{A,b}	0.44 ± 0.18 ^{A,a}	0.44 ± 0.24 ^{A,a}	0.38 ± 0.20 ^{A,a}	0.47 ± 0.19 ^{A,a}	0.38 ± 0.19 ^{A,b}	0.41 ± 0.34 ^{A,a}
Daily Qc ($l\ d^{-1}$) **per coffee tree**	1.20 ± 0.52 ^{A,b}	1.41 ± 0.77 ^{A,b}	0.86 ± 0.45 ^{A,b}	1.38 ± 0.56 ^{A,a}	1.57 ± 0.84 ^{A,a}	1.00 ± 0.54 ^{A,a}	1.47 ± 0.58 ^{A,a}	1.33 ± 0.68 ^{A,b}	1.06 ± 0.90 ^{A,a}

*Number of days in which data is available for at least three replicates. Days with less than 2 replicates were not included in the analysis.
**SWA (*Coffee-CO* = 12.7 ± 2.5 cm^2, *Coffee-CB* = 10.0 ± 1.6 cm^2 *and Coffee-CC* = 10.5 ± 3.2 cm^2).
***N°stems per coffee tree (*Coffee-CO* = 3.1 ± 0.9, *Coffee-CB* = 3.5 ± 1.2 *and Coffee-CC* = 2.6 ± 0.9).

and higher values of Js were reached during the late dry period (supplementary material, figure A.4). Coffee in contrast showed initially an increase until a VPD threshold of around 2–3 kPa was achieved, whereas Js was maintained or reduced with further increases in VPD. This pattern was consistent across all systems and periods. Nevertheless, when VPD was below 2 kPa, Coffee-CB and Coffee-CC reached higher values of Js compared to Coffee-CO during the wet period (Fig. 2). Js patterns of *C. africana* showed a poor correlation with VPD for all the different periods, and Js tended to be larger at lower VPD during the early dry period (supplementary material, figure A.4).

4. Discussion

Coffee water consumption per tree, with 1.2 ± 0.64 l d^{-1}, was similar across cultivation systems with an increase during early and late dry periods, when VPD increased. Consequently, we could not observe a system effect on coffee water use, and hence hardly any signs of water competition between coffee and associated shade species. This was most likely due to the fact that rainfall amount and SWC were sufficient to meet water requirements of the studied systems. Daily water use per tree was lower in bananas than in *C. africana*, but daily transpiration rate per ground area and unit leaf area were larger for bananas (Fig. 4). Daily system transpiration was higher in CB than in CC and CO (Fig. 4), due to higher coffee plant densities than CC and CO, and the higher banana densities than the one of *C. africana*.

Temperature during the late dry period surpassed critical thresholds of optimum temperature (Tmean between 18 °C and 22 °C and Tmax below 30 °C) range for *C. arabica* according to Descroix and Snoeck (2008), even under shaded systems. Compared to CO and CB, CC reduced incoming radiation and showed better buffering effects against extremes (Ta max and Ta min) and, hence had smaller daily temperature amplitude (Ta max – Ta min). Shade trees consequently protected the coffee underneath from high temperature and high radiation; and reducing coffee leaf area oscillations between seasons. CC on the other hand, lowered SWC in comparison to CO and CB, which might result in water competition under drier conditions than experienced in our study. Detailed discussion of various factors follows below.

4.1. Microclimate differences between cultivation systems

The microclimate regulating role of shade trees has already been described by several authors (Barradas and Fanjul, 1986; Muschler and Bonnemann, 1997; Siles and Vaast, 2002; Partelli et al., 2014; Carvalho et al., 2017) and was confirmed by the present results. Nevertheless, when examining the three defined periods, it was found that the differences in VPD between systems were very low (around 0.1 K Pa), and not always significant. We attributed this to the patchiness at landscape level with a close proximity of the various systems within neighboring small farms. Our findings confirmed the importance of studying microclimate at different temporal resolutions to identify if at certain hours of the day, relevant coffee physiological thresholds such as VPD > 2 kPa, are reached and the time span that such microclimate conditions last. This is of interest since intensity, duration and speed of certain stresses will influence the plant acclimation ability, and therefore their coping capacity against stresses (DaMatta and Ramalho, 2006).

The reduced SWC in the upper layers (0–40 cm) in all systems, confirmed that coffee soil water uptake occurs mostly in the top 40 cm of the soil profile, although it could extend down to 70 cm. This is in congruence with Padovan et al. (2015), who reported that 56% of coffee roots were encountered in the upper 30 cm and was also reported in other studies (Wallis, 1963; Pereira, 1957; van Kanten et al., 2005; van Kanten and Vaast, 2006). Water uptake by *C. africana* was mainly concentrated in the top 90 cm, extended even down to 130 cm depth during the dry periods (early and late dry) (Figs. 3 and 4). This indicates that the first 40 cm were overlapping with the active coffee root zone,

Table 4
Mean Js and Daily Qc for bananas and Cordia africana for Wet (April, May, Jun, Sep, Oct and Nov 2015, April 2016), early dry (July, Aug and Dec 2015, Jan 2016) and late dry (March 2015, Feb and March 2016). Capital letters indicate significant differences between species (Banana and Cordia africana) for each period. Small case letters indicate significant differences across periods within each species at p-value < 0.05.

	Banana			*Cordia africana*		
	Wet	Early dry	Late dry	Wet	Early dry	Late dry
N° Monitoring Days	69	49	110	102	85	153
Mean Js ($g\ cm^{-2}\ h^{-1}$)	2.05 ± 1.07 ^{A,c}	3.16 ± 1.80^{A,b}	3.52 ± 1.86 ^{A,a}	1.96 ± 0.86 ^{A,a}	2.16 ± 1.41 ^{A,a}	1.95 ± 1.25 ^{A,b}
Daily Q ($l\ d^{-1}$)	2 ± 1 ^{B,c}	3 ± 2 ^{B,b}	4 ± 2 ^{B,a}	39 ± 30 ^{A,b}	45 ± 46 ^{A,a}	41 ± 45 ^{A,b}

*Number of days in which data is available for at least three replicates. Days with less than 2 replicates were not included in the analysis.
**SWA (Banana = 76 ± 20 cm^2, C. africana = 1061 ± 921 cm^2.

which reduced soil water content of CC system compared to CB and CO. Consistent lower values of SWC in heavy shaded systems in comparison with low shaded or non-shaded systems have also been reported by Siles et al (2010) and Padovan et al (2015), which they explained as a result of higher combined transpiration of coffee and shade trees under high shade. This is also the case in our study (Fig. 4).

Nevertheless, despite larger transpiration in CB than in CC, we found lower SWC in CC during all seasons (Fig. 3 and Table 3) We attributed this to a better water use efficiency in the CB system due to an effect of the intermediate shade of the bananas. It is hypothesized that banana shade reduced soil evaporation of upper layers, and intercepted less rainfall than *C. africana* trees, hence allowing higher soil water availability for coffee and banana transpiration. Moreover, the aspect of the plot (slope > 20%) and distribution of systems along the slope (CC at the highest point and CB at the lowest point, see supplementary material figure A.2) could have influenced water redistribution (runoff and lateral infiltration), increasing soil water content in CB. Nevertheless, clearly, additional data, such as soil evaporation rates, run-off, lateral infiltration and rainfall interception would be required to prove these hypotheses.

4.2. Sap flux density, water use and transpiration

Sap flux density (J_s) of coffee under all systems as well as *C. africana* decreased when VPD was > 2 kPa, which can be attributed to stomatal sensitivity to high VPD. In the case of coffee, this threshold has already been reported in several studies (Butler, 1977; Fanjul et al., 1985; Gutierrez et al., 1994; Kanechi et al., 1995; Carr, 2001; DaMatta and Ramalho, 2006; van Kanten and Vaast, 2006). Also in other woody species, such as *Ulmus davidian, Terminalia ivorensis* and *Eucaliptus deglupta*, a similar VPD threshold could also be observed (van Kanten and Vaast, 2006; Jung et al., 2011). On the contrary, banana followed a linear increase with increasing VPD without an observable threshold, thus without stomatal control. These results are in line with patterns described by Lu (2002) and Liu et al (2008).

Daily coffee water use did not differ significantly between systems (Table 4), which can be attributed to several factors. Firstly, although significant, differences in VPD between systems were in the range of 0.2 kPa, which might be too small to generate any system-specific response in Js for coffee. Secondly, hourly VPD values frequently crossed the 2 kPa threshold in all systems, therefore restricting increases in coffee Js, and subsequently in coffee Q_c. Thirdly, as a shade-adapted species, coffee maintains stomatal conductance, thus photosynthetic rates, and water use (DaMatta and Ramalho, 2006; Franck and Vaast, 2009), even at reduced irradiance as in the case of CB and CC. Finally, a high variability in J_s between individuals within the same system, as indicated by the high standard deviation, certainly hindered to some extent the system comparison.

Similarly, coffee transpiration per unit leaf area did not significantly differ between systems. Nevertheless, coffee transpiration per unit leaf area had different seasonal responses depending on the system. Coffee-CO and Coffee-CB increased transpiration per unit leaf area during the late dry period, while Coffee-CC increased during the wet period. Such variations can be attributed to the increase of J_s during the late dry period combined with the reduction of the coffee LAI up to 40% and 15% in the case of Coffee-CO and Coffee-CB, respectively (Fig. 4). LAI in Coffee-CC increased during the early and late dry periods by 10% compared to the wet period. Maintenance of coffee sap flow rates despite changes in leaf area were also reported by Tausend et al. (2000).

We attributed LAI reduction in Coffee-CO to a combined effect of high irradiance and VPD, on top of large air Ta diurnal variations, which could have increased leaf damage and reduced leaf growth (Gutierrez et al., 1994; Siles and Vaast, 2002; DaMatta and Ramahalho, 2006). The transpiration rates per leaf area recorded during our study remained low compared to the ones reported by Padovan et al. (2018). As well as coffee LAI and coffee tree density per hectare recorded in our study was half when compared to 4700–5000 tree ha^{-1} and coffee LAI = 4.6 in full sun reported by Cannavo et al. (2011). And 4000 trees ha^{-1}, coffee full sun LAI = 2.39 ± 0.10 SE shaded coffee LAI = 3.57 ± 0.10 SE reported by Padovan et al. (2018).

To our knowledge, our study is the first aiming to estimate water use of *C. africana* with thermal dissipation probes. *Cordia africana* was found to consume 10 times more water per day than banana and 100 times more than coffee, which can be mainly attributed to its larger canopy size and sap wood area. Nevertheless, when normalized by unit leaf area, lower transpiration per unit leaf area for *C. africana* than for coffee or banana was observed. On average, *C. africana* consumed similar amounts of water as other deciduous shade species such as *Tabebuia rosea* with 60 to 170 l d^{-1} (Padovan et al., 2018). Transpiration per ground area of *C. africana* (0.16 ± 0.16 mm d^{-1}, 50 trees ha^{-1}) was lower than transpiration per ground area reported for *Inga densiflora* (0.49 ± 0.5 mm d^{-1}, 277 tree ha^{-1}) reported by Cannavo et al. (2011), *Simarouba glauca* (0.20 ± 0.02 SE mm d^{-1}, 75 trees ha^{-1}) and *Tabebuia rosacea* (from 0.24 mm d^{-1} to 1.05 mm d^{-1}, 113 trees ha^{-1}) reported by Padovan et al. (2018). Banana, on the other hand, had comparable transpiration per ground area (0.34 ± 0.20 mm d^{-1}, 975 mats ha^{-1}) to the above mentioned species, although at higher densities per hectare.

Despite no significant differences in coffee daily water use between systems were observed and water competition appeared to be absent due to sufficient rainfall, extended periods without rain and a decrease in rainfall amount, could pose a problem for coffee when intercropped with other species. This became visible in the lower soil moisture content in shaded systems, particularly CC and is in line with the observations by Cannavo et al. (2011); Padovan et al. (2015), and Padovan et al. (2018). Our results showed that transpiration rates of coffee and agroforestry systems appeared to be highly dependent on system structure (coffee density and shade trees density, LAI and tree size), and hence difficult to compare across regions. Therefore, we recommend the reporting of transpiration rates per ground and leaf area,

accompanied with water use per tree (Q_c), size of individuals, LAI and density per ha, to provide a comprehensive description of water use in coffee agroforestry systems.

CB had the highest transpiration rates due to the high coffee tree density, in addition to a linear response of banana J_s to vapor pressure deficit, under non soil water limiting conditions. Bananas lack a water saving mechanism under high evaporation demand, as demonstrated by the high J_s rates at high VPD values of our study (Fig. 2). This could lead to faster soil water depletion and water competition between coffee and bananas. Nevertheless, we could not demonstrate this hypothesis in our study, since rainfall appeared to be enough to sustain transpiration demand of all studied systems and no water limitation was observed. Furthermore, other studies indicated that despite the fact that banana sap flux density responses linearly to VPD, bananas are very sensitive to reduced SWC (pF > 2.8), thus reducing water use at low soil water content (Kissel et al., 2015).

This would mean that under soil water scarcity, bananas would reduce their water use. However it remains to be documented if this transpiration reduction would appear early enough to avoid water competition with associated coffee and hence become an attractive climate-smart adaptation strategy. Clearly, CB systems are of particular interest since bananas are the most important staple crop in the region and provide farmers with food and extra source of income (van Asten et al., 2011). Furthermore, due to fast banana growth, coffee intercropped with banana allows for a more dynamic shade management than coffee intercropped with woody shade trees. Indeed, farmers could voluntarily cut down banana if the dry season becomes too severe and detrimental to coffee. Further research is required to assess the water dynamics of these systems under harsher conditions, namely lower annual rainfall and prolonged dry season.

4.3. Caveats of the study and future recommendations

We acknowledge that the heterogeneity of the studied systems, in terms of structure: slope, distribution along the slope, coffee tree density and shade tree density could certainly interfere in our comparison of the systems. It has to be kept in mind, however this study was performed under on-farm conditions and high variability is inherent to research within smallholder farmers' conditions. Furthermore, water use experiments require certain compromises due to technical restrictions, namely availability of a power source and distance to the data logger. Nevertheless, we presented in this study, not only transpiration at system level, but as well at individual level and the scaling factors used in order to account for these differences in system structure. Presentation of these parameters helps understanding how system structure might influence transpiration rates of agroforestry systems. Furthermore, we strongly recommend this to become a common practice in water use studies of agroforestry systems, where, as pointed out before, systems structures can be very diverse.

Additionally, we propose for future research activities to expand the period of time, over which water use patterns are monitored to several seasons and years. Moreover, we propose to consider other shade tree species commonly used (e.g. *Ficus* sp., *Persea americana*, *Grevillea robusta*, *Markhamia indica*) at Mt Elgon (Rahn et al., 2018). Furthermore, sap flow techniques should be combined with other measurements, such as stomatal conductance, photosynthesis, and leaf water potential, to include more indicators of coffee stress. Finally, high variability in J_s between trees should be addressed by increasing the number of monitored trees per system, as well as increasing the number of plot replicates.

5. Conclusion

To our knowledge, this is the first study investigating jointly the water use patterns of *Coffea arabica, Musa sp* and *Cordia africana* in the context of agroforestry systems in Africa. Our results are valuable to support farmers in managing their coffee farms and inform extension services and other stakeholders aiming to adapt coffee cultivation to climate change as well as food security and livelihoods of smallholder coffee farmers in particular in Eastern Africa.

In the present study, we found no competition for water between coffee and banana, or coffee and *C. africana,* since coffee water use remained similar across systems. Shade trees modified the microclimate for coffee underneath by reducing total soil water content, incoming radiation, maximum temperatures and temperature amplitude, and by increasing minimum temperatures. Despite the fact that the microclimate-buffering effects of shade trees were reduced during the late dry period, shade trees still benefited coffee by reducing the combined, negative effect of high radiation and high VPD on leaf growth and integrity.

Nevertheless, under more extended dry seasons, water competition between coffee and banana or *Cordia africana*, might occur due to the higher combined transpiration of coffee and associated shade plants in agroforestry systems compared to open system. The Coffee-Banana system is an attractive cultivation system since banana reduces solar radiation, VPD and maximum temperatures for coffee underneath, while providing food and an extra cash sources to rural households. Furthermore, fast banana growth allows dynamic density management to reduce water competition with coffee in case of need, i.e. a particular prolonged dry season.

Based on this study addressing water relations, we recommend the cultivation of coffee underneath medium shade (20–40 %), the careful selection of shade species, either for its contribution to income or food security (as in the case of banana) or for its physiological characteristics (reduced water use under water limited conditions and fast growth) or morphological characteristics (rooting depth below 80 cm and hence below the main coffee rooting zone). Furthermore, farm management activities such as mulching, pruning and thinning should be combined with weather forecast to tailor the system water demand to the soil water availability of the season.

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Appendix A. Supplementary data

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